INITIATION OF CONDENSED EXPLOSIVES BY GAS DETONATION

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Introduction

There are two ways in which stimuli may induce detonation in secondary explosives. A strong shock may cause detonation with an induction time of a few microseconds, i.e., time intervals of a few microseconds between application of the stimulus and the appearance of detonation. A weaker shock or a purely thermal stimulus may initiate reactions that begin as a deflagration and accelerate to detonation. The acceleration of the reaction occurs as a consequence of increasing pressure, or self-pressurization, produced by the hot, gaseous decomposition products. Maintenance of pressure for periods of 10's to 100's of microseconds, as may be required to obtain detonation from weak initiation stimuli, is achieved by confinement of the explosive sample.

Although such confinement is usually provided by high-strength metallic containers, for short periods of time it can also be a consequence of inertial effects. If low-strength confinement surrounds the explosive sample the acceleration of the confinement material is directly proportional to the pressure seen by the explosive sample and inversely proportional to the confinement mass per unit area of explosive sample. At early times, the expansion and escape of product gases are limited by the low velocity of expansion of the container and self-pressurization of an explosive sample may be maintained for considerable periods. Inertial confinement, or self-confinement might be provided by a large pile of explosive to a reaction initiated within the interior of the pile.

Examples of the first type of stimulus are initiation by other condensed phase explosives and by projectile impact. Initiation of detonation in condensed explosives has been studied using strong shocks across air gaps[1] or through inert barriers[2,3] and by determining projectile impact initiation parameters.[4,5,6] Threshold initiation shock pressures for condensed explosives range from 1 to 100 kbar. An example of the second type of stimulus is that of thermal ignition transforming to detonation in the confined explosive.[7,8]

This paper describes results obtained with an initiation source producing a stimulus that is continuously variable from less than that required to ignite explosive flours to more than that required to detonate pressed pellets. The initiation source is the detonation wave produced in gaseous mixtures of stoichiometric ethylene-oxygen ($C_2H_4 + 3\ O_2$).

Until recently, gas detonation waves free from incandescent solid debris had to be obtained by run-up in a detonation tube.[9,10,11,12] Such tubes were economically unattractive, inconvenient in use, or restricted in use by the run-up characteristics of the gaseous mixture. In Bureau of Mines' studies, gas detonations have been obtained without run-up in a detonation tube and without explosive detonators.[13]

One possible difference between the shock from a projectile and the gas detonation shock is the difference between a "cold" and a "hot" shock. In the first case, temperature increase in the condensed explosive sample is entirely a consequence of mechanical interactions and conversion of translational energy into heat. In the second case, there is additional thermal energy in the hot ethylene-oxygen combustion

products. Phenomenological analysis and experimental results indicate that the transport from the hot gases is negligible when the explosive is initiated within 1 μ sec.

Experimental Procedures

The test container was a 17.8 cm length of 1-inch schedule 80 pipe, reamed to an inside diameter of 2.54 cm. Explosive samples were positioned at one end of the tube and the wires to initiate the gas detonation were positioned near the other end.

The detonable gas mixture was 25 percent ethylene and 75 percent oxygen as determined by partial pressures. Gases were injected into the evacuated chamber through 1/16-inch orifice fittings for mechanical mixing and 20 minutes was allowed for additional diffusional mixing. Gases were from commercial cylinders and were used without further treatment. Initial pressures of the prepared gas mixture were from 3 to 85 atm gage. Initial pressures less than 3 atm were obtained by reducing a 3-atm mixture to the desired pressure.

To initiate the gas, a 0.15 mm (No. 35 B&S) copper wire, 2 cm long, was exploded with the discharge from a 1.5 μf condenser charged to 5.5 kv or more (25 joules energy, or more) using a hydrogen thyratron switch. Control trials in which the wire was exploded with inert gas plus condensed explosive gave no evidence of debris impingement or reaction of the explosive.

Representative particle size analyses of the floured or granulated materials are given in table 1. Particle sizes and distributions under the test conditions may have been slightly different. Gas was injected through orifices to produce turbulent, circulatory gas mixing. This injection must have disturbed the surfaces of the unpressed samples with some increase of "fines" occurring at the top of the sample.

The unpressed flour or granulated samples were prepared by pouring a standard weight of material into the test vessel and tapping lightly to level the sample surface. Standard weights were: 10 gm PETN,* 10 gm RDX,** 13.2 gm tetryl,*** or 14 gm Composition A5.**** Direct determinations of possible densities in the tested charges of floured or granulated explosive have given: for PETN - 0.40 to 0.69 gm/cc; for neat RDX - 0.67 to 0.91 gm/cc; for Composition A5 - 0.93 to 1.02 gm/cc; and for tetryl - 0.93 to 1.14 gm/cc. As initially prepared in the test vessel, densities were near the larger figure in all cases and these are the numbers quoted in the tables. The particle size distributions of table 1 imply adequate porosity to permit pressure equilibration within the floured or granulated sample by gas flow during loading of the detonable gas mixture. Thus, the gas charging pressure would not affect, per se, the density of the charges. As was the case with particle size data, the effect of the gas jet mixing action upon the charge density is not known.

Pellets of Composition A5 and of tetryl were prepared and tested at pellet densities of 1.6 gm/cc and 1.4 gm/cc. Pellets of PETN + 1 percent graphite were tested at densities of 1.6 gm/cc. All pellets were 1 inch long. Comparative tests of PETN and PETN + 1 percent graphite, both in flour form, did not reveal any noticeable difference in sensitivity resulting from the graphite addition.

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* Pentaerythritol tetranitrate.
** Cyclotrimethylenetrinitramine (hexahydro-1,3,5 trinitro-s-triazine).
*** 2,4,6-trinitrophenylmethylnitramine.
**** RDX + 1% stearic acid coating material.

Measurements were made of the pressure-time history at the initial explosive surface until detonation, location of first appearance of significant reaction, and the propagation velocity on the axis. These data were obtained from resistive pressure transducers[14] and continuous wire probes.[15]

The resistive transducer was a composition resistor of 0.1 watt rating. The variation of resistance with loading pressure has been established in Bureau of Mines investigations.[14] The approximate constancy of the calibration over periods of about 100 μsec after application of the gas detonation shock stimulus has been established in one instance by direct comparison with strain gage measurements. This result provides justification for reading a "pressure at detonation" at the time that detonation is shown by the velocity probe.

The wire probe consisted of a fine, nichrome axial wire helically wound with a nylon filament for insulation from the surrounding, collapsible aluminum tube. Collapse of the aluminum tube altered the probe resistance and gave a direct indication of the physical location of the shorting point. Rates of change of the probe resistance were proportional to the velocities of the pressure front. For trials at charging pressures greater than 14 atm gage, the probe record displayed the time-position loci in both the gaseous and the solid phases.

Results

The explosive flours or granules were observed to react in three different ways depending upon the explosive and the gas charging pressure. At higher gas charging pressures, supersonic reaction was induced with a time delay ≤1 microsecond. At lower pressures, significant chemical reaction was evident only after a delay of several microseconds and detonation commenced at some distance below the original surface of the explosive sample. At still lower pressures, granular tetryl or Composition A5 was not initiated to self-sustaining chemical reactions even though a portion of the sample might have been consumed in the test.

Test results are summarized in table 2 where charging pressures are given for the reaction modes of the several samples. PETN flour samples at a density of 0.7 gm/cc required detonable gas mixture charging pressures of 20 atm, gage, to initiate detonation with induction times ≤1 μsec. At charging pressures of 0 atm gage the flour was initiated to lower order reaction and transited to detonation after considerable delay (≥200 μsec). When pressed to a density of 1.6 gm/cc, PETN required charging pressures of 85 atm gage to produce detonation within 1 μsec of the impact of the detonation wave. At charging pressures less than about 9 atm gage, the 1.6 gm/cc PETN pellet was not initiated to self-sustaining reaction.

The initiation sensitivity for RDX and tetryl also reduced with increasing density as would be expected. In the unpressed, flour or granule form the ordering of the sensitivities, S, is

$$S_{PETN} \left[\rho = 0.7 \text{ gm/cc} \right] > S_{RDX} \left[\rho = 0.9 \text{ gm/cc} \right] > S_{tetryl} \left[\rho = 1.0 \text{ gm/cc} \right] ;$$

this ordering appears applicable to both the production of detonation with ≤ 1 μsec delay and to the failure to produce a self-sustained reaction. The same ordering of sensitivities appears to apply when pressed pellets of nearly equal density are compared; and is the same ordering as found by drop-weight impact[16] and by projectile impact.[6]

The detonation velocities observed in the present tests were similar to those reported by Hampdon and Stresau[17] with the qualifications noted by Jones and Mitchell.[18] With a gas charging pressure of 2 atm gage, PETN flour was initiated to a velocity of 3.5 mm/μsec after a delay of 4 μsec; 8 μsec later this velocity accelerated to the stable value, 4.8 mm/μsec. When RDX flour was initiated to

detonation with 12 atm gage gas charging pressure, the initial velocity was about 2.6 mm/μsec; after 4 μsec, acceleration to the stable velocity, 5.4 mm/μsec, occurred. With 2 atm gage charging pressure, a subsonic reaction rate of 0.3 mm/μsec in the RDX accelerated to the stable value, 5.4 mm/μsec, after 30 μsec. With 16 atm gage, tetryl flour was initiated at a velocity of 2.8 mm/μsec, and with 6 atm gage, 1.55 mm/μsec was observed. Acceleration to the stable, high rate of 5.3 mm/μsec did not occur. This result is presumed to be a consequence of the dimensions of the explosive sample.[18]

When detonation occurs after induction times of several microseconds, it is to be expected that details of the hot gas-solid explosive-confinement interactions are important in determination of the course of the reaction. It was observed that after the initial pressure pulse impingement, the pressure remained nearly constant for several microseconds and then increased at a high rate. The high rate of pressure increase is seen first as a series of spikes probably due to individual pressure wave interactions followed by an approximately exponential rise to quite high values of pressure. The high values of pressure in the container following the exponential rise are of the same order as detonation wave pressures to be expected in the condensed sample.

Associated with incidence of the approximately exponential rate of increase in pressure, was an increased rate of propagation as shown by the velocity probe. Comparison of records obtained with various initial gas charging pressures showed that the pressure at appearance of the high rate could be correlated with the explosive density and with the explosive type. As an example, with PETN flour and a charging pressure of 0.7 atm gage, the induction time was 24 μsec and the vessel pressure at appearance of detonation was about 2 kbar. With the same type of explosive sample but a charging pressure of 20 atm gage, the induction time was about 1 μsec and the pressure in the vessel at appearance of detonation was again about 2 kbar. This type of observation of a critical pressure for the occurrence of detonation is supported by the results of Price, Wehner, and Roberson.[7]

Table 3 compares pressures for the appearance of detonation as determined in this study, to the shock pressure required to initiate unconfined charges as given by, or derived from, the results of other investigations.[2,4,5,6,19] The reasonable conformity of measured values from such diverse techniques strongly suggests that the tabulated pressures are indeed critical pressures for the occurrence of detonation. The individual values of table 3 and of table 4 are offered as representative data. Additional experience with the sensors and additional experimental data are required before the results are considered to be more than semiquantitative.

Application of Results to a Large Pile of Explosives
Under Conflagration Conditions

A. Assumed Stimulus is a Gas Detonation External to the Pile

The stoichiometric mixture of ethylene and oxygen must be charged to pressures of 20, 26, or 26 atmospheres respectively in order that the gas detonation be able to induce detonation in PETN, RDX, or tetryl flours with delay times of about 1 μsec. Buildings, bins, or containers capable of withstanding more than 275 psig are economically and architecturally incompatible with the storage of tons of explosives.

Concern, then, is entirely with pressures of approximately zero psig for such a detonable gas mixture. Table 4 summarizes induction times as functions of detonable mixture charging pressure for PETN and RDX. (According to table 1, tetryl was not initiated to detonation at charging pressures below 3 atm gage.) Induction times of PETN and RDX, at 1 atm charging pressure, are $\geq$ 200 and 250 μsec respectively. Detonations produced in sufficiently large external volumes of gas could

maintain the gas stimulus at the explosive surface for these, or longer, periods of time[20] but such "gas detonation confinement" would not support the relatively slow buildup of pressure to values in excess of the critical pressure for appearance of detonation (more than 28,000 psi). One test with 1.1 gm/cc, Composition A5 explosive showed transition directly from a level of about 2000 psig in the container without observable pressure run-up in the gas phase close to the explosive surface. However, 2000 psig is beyond the range of sustained pressures available from an unconfined gas detonation.

It is thus improbable that an external, unconfined, gas detonation would cause direct initiation of a large pile of flour explosives of the types tested. If the gas detonation were to produce fragments having velocities of 300 m/sec or more[6] such fragments might produce detonation in the large pile. Existing data on projectile initiation are not sufficiently complete to permit numerical prediction of gas volume versus projectile size and velocity relationships.

B. Assumed Stimulus is Internal to the Large Pile of Explosives

Peak pressure in the reflected gas detonation wave, of these studies, at 0 psig is believed to be less than 0.2 kbar; the Chapmen-Jouguet pressure is even lower, of course. In view of the appreciable difference between these pressures and the critical pressure required for appearance of detonation in the condensed phase, it is probable that the initiation sequence is that of ignition of the explosive particles and then self-pressurization of the test vessel by the decomposition products. The exact mechanism by which deflagration of the explosive particles is initiated, whether by an enthalpy wave, by an internal autoignition of "cook off" gases, or by an external flame, is not of particular importance. The important question is whether or not adequate confinement is provided to permit the pressurization to occur. Two circumstances can be postulated to provide the necessary confinement by an explosive pile--collapse of a cavity formed by erosion, or enfoldment of burning particles by a sliding pile. Because of lack of knowledge about ullage space--induction time relationships and because of the complicated dynamics of the mechanical collapse or enfoldment, it is not presently possible to discuss these circumstances in detail. It may be of academic interest to note that rigid collapse of a 5-meter-high pile of material having a sonic velocity of 2000 m/sec would provide nearly rigid confinement for a time of 200 μsec.

Summary and Conclusions

Gas detonations generated in stoichiometric ethylene-oxygen mixtures have been used to produce detonations in PETN, RDX, and tetryl explosive. The explosive has been tested both as a flour and as pressed pellets. The experimental results suggest the existence of a critical pressure for the appearance of detonation in the condensed explosive. Induction time does not have a strong effect upon the induction pressure--the pressure to which the explosive is subject at the time of appearance of detonation. These induction pressures were sensitive to explosive type, density, and particle size. From these results, it has been deduced that a gas detonation cannot produce detonation of a large pile of these materials without the interposition of some action producing confinement of the ignited explosive grains. The requisite confinement cannot be provided by an unconfined gas detonation.

Induction pressures for the tested flours or granules of PETN, RDX, and tetryl were 2, 3, and 3 kbar respectively. In pressed pellets, pressures for appearance of detonation were: 13 kbar for 1.6 gm/cc PETN; 12 kbar for 1.4 gm/cc Composition A5; 16 kbar for 1.6 gm/cc Composition A5; 16 kbar for 1.4 gm/cc tetryl; and 20 kbar for 1.6 gm/cc tetryl.

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TABLE 1. - Particle size distributions of
explosive flours or granules

Particle size range R, microns	Percent of sample in range			
	PETN	RDX[1]	RDX[2]	Tetryl
710 < R	7	2	1	14
350 < R < 710	81	20	85	79
105 < R < 350	7	63	13	6
74 < R < 105	0	2	1	0
R < 74	0	15	0	2

[1]/Neat RDX.
[2]/RDX + 1% stearic acid (Composition A5).

TABLE 2. - Threshold charging pressures of stoichiometric
ethylene-oxygen mixtures to produce gas detona-
tion initiation of detonation in PETN, RDX, and
tetryl

Explosive	Density, gm/cc	Detonation with $\leq 1\,\mu$ sec delay, atm gage	No detonation atm gage
PETN	0.7	20	< 0
PETN[1]/	1.60	85	[3]/ 9
RDX	.9	26	< 0
RDX[2]/	1.1	80	8
RDX[2]/	1.40	84	[3]/ 15
RDX[2]/	1.64	> 84	[3]/ 39
Tetryl	1.0	26	[3]/ 3
Tetryl	1.39	> 85	[3]/ 39
Tetryl	1.57	> 85	[3]/ 67

[1]/ 1% graphite added.
[2]/ 1% stearic acid added.
[3]/ Average from lowest value for detonation and highest value for no
detonation.

TABLE 3. - <u>Comparison of minimum shock pressures for initiation of explosive compounds by gas detonation or for initiation with the indicated stimulus</u>

Source	Density, gm/cc	Type of Stimulus	Shock Pressure, kbar
		PETN	
This work	0.7	Gas detonation	1/ 2.1 $\pm$ 0.3
LeRoux	0.7	Projectile impact	2/ 2.0
Seay and Seely	1.0	Plane shock wave	2.5
Weiss and Litchfield	1.48	Projectile impact	11.0
Eldh and coworkers	1.53	Projectile impact	2/11.0
This work	1.60	Gas detonation	1/13.3 $\pm$ 0.5
		RDX	
Weiss and Litchfield	0.8	Projectile impact	3.0
This work	.9	Gas detonation	1/ 3.1 $\pm$ 0.4
LeRoux	1.0	Projectile impact	2/ 3.0
This work	1.1	Gas detonation	3.4 $\pm$ 0.5
This work	1.40	Gas detonation	12.
This work	1.64	Gas detonation	1/16. $\pm$ 1
Weiss and Litchfield	1.62	Projectile impact	21.0
Eldh and coworkers	1.65	Projectile impact	2/22.0
		Tetryl	
This work	1.0	Gas detonation	3/ 3.
Weiss and Litchfield	1.00	Projectile impact	3.5
LeRoux	1.00	Projectile impact	2/ 3.5
This work	1.39	Gas detonation	3/11.
Weiss and Litchfield	1.57	Projectile impact	19.0
This work	1.57	Gas detonation	13.
Eldh and coworkers	1.65	Projectile impact	2/22.0

1/ Mean and estimated standard deviation per observation.
2/ These values calculated by the authors from projectile velocity data of other investigators.
3/ For low-velocity detonation.

TABLE 4. - Summary of parameters for initiation of flour and pelletized explosive compounds by gas detonation

Explosive	Density gm/cc	Charging pressure, atm gage	Container pressure at detonation, kbar	Induction time, μsec
PETN	0.7	0.0	--	≥200
PETN	.7	0.7	2.2	28
PETN	.7	1.0	--	8
PETN	.7	1.7	--	5
PETN	.7	2.1	--	4
PETN	.7	3.1	1.9	6
PETN	.7	20.0	--	1
PETN	1.60	54.0	13.0	4
PETN	1.60	85.0	13.5	1
RDX	0.9	0.0	--	≥270
RDX	.9	1.0	--	50
RDX	.9	1.4	--	56
RDX	.9	1.7	--	28
RDX	.9	3.1	--	12
RDX	.9	5.9	--	5.7
RDX	.9	20.0	3.3	4
RDX	.9	26.0	2.9	1
RDX[1]	1.1	11.2	6.0	70
RDX[1]	1.1	11.2	4.0	72
RDX[1]	1.1	27.2	3.1	36
RDX[1]	1.1	40.4	3.0	16
RDX[1]	1.1	58.0	3.4	7
RDX[1]	1.1	80.0	--	1
RDX[1]	1.40	50.0	--	7
RDX[1]	1.40	84.0	12.5	1
RDX[1]	1.64	57.0	17.0	14
RDX[1]	1.64	82.0	15.0	4

[1] RDX + 1% stearic acid (Composition A5).